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Gauging the baryon density of the Universe from an improved rate of deuterium burning

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Among the light elements produced during Big Bang Nucleosynthesis[1,2] (BBN), deuterium is an excellent indicator of cosmological parameters because its abundance is highly sensitive to the primordial baryon density and also depends on the number of neutrino species permeating the early Universe. While astronomical observations of primordial deuterium abundance have reached percent accuracy[3], theoretical predictions[4–6] based on BBN are hampered by large uncertainties on the cross section of the deuterium burning $D(p,\gamma)^3He$ process. Here we show that our improved cross sections finally allow for BBN estimates of the baryon density at the 1.6% level, in excellent agreement with a recent analysis of the Cosmic Microwave Background[7]. Improved cross-section data were obtained by exploiting the negligible cosmic-ray background deep underground at the Laboratory for Underground Nuclear Astrophysics (LUNA) of the Laboratori Nazionali del Gran Sasso (Italy) [8,9]. We bombarded a high-purity deuterium gas target[10] with an intense proton beam from the LUNA 400 kV accelerator[11] and detected the γ rays from the nuclear reaction under study with a high-purity germanium detector. Our experimental results settle the most uncertain nuclear physics input to BBN calculations and substantially improve the reliability of using primordial abundances as probes of the physics of the early Universe.

Light elements were produced in the first few minutes of the Universe through a sequence of nuclear reactions known as Big Bang Nucleosynthesis (BBN)[1,2]. The theoretical description of BBN is based on the standard cosmological model (hereafter the "ΛCDM model"[2]), which assumes a homogeneous and isotropic universe governed by general relativity and by the Standard Model of particle physics. Under these assumptions, BBN predicts the abundances of primordial nuclides, mainly ^{2}H (hereafter D), ^{3}He, ^{4}He, and ^{7}Li, as a function of one parameter only, the density of ordinary matter, or baryon density, $\Omega_\mathrm{b}h^2$ (see Fields *et al.*[12] for a recent review). Therefore, a comparison between the observed primordial abundances and those predicted by the BBN can be used to constrain this fundamental quantity. Yet an independent evaluation of $\Omega_\mathrm{b}h^2$ can also be obtained by measuring the anisotropies in the Cosmic Microwave Background (CMB), the relic electromagnetic radiation left over from the Big Bang.

It should be noted that $\Omega_\mathrm{b}h^2$ from the CMB reflects the baryon density of the Universe at the re-combination epoch, some 380,000 years after the Big Bang. However, according to the ΛCDM model, the baryon density can only vary as a result of the expansion of the Universe and thus its present-day value inferred from either CMB and BBN should be the same. Therefore, the evaluation of $\Omega_\mathrm{b}h^2$ based on BBN alone is critical as it can either support the ΛCDM model or point to new physics between the BBN and CMB epochs[2]. We present a new evaluation of $\Omega_\mathrm{b}h^2$ from BBN based on improved experimental nuclear physics inputs obtained at the Laboratory for Underground Nuclear Astrophysics (LUNA)[8,9] of the INFN Laboratori Nazionali del Gran Sasso (Italy).

Of the elements produced during the BBN, deuterium (D) is an excellent indicator of cosmological parameters in the early Universe because its abundance is the most sensitive to the baryon density $\Omega_\mathrm{b}h^2$ and also depends on the radiation density, usually expressed in terms of the effective number N_eff of neutrino species[2]. Since deuterium is almost exclusively produced during

BBN, and is only destroyed during stellar evolution, its primordial abundance can be obtained from astrophysical sites not affected by stellar evolution[4]. The best determination of the deuterium abundance is presently obtained by analysing the light spectra of quasars crossing pristine gas clouds at high redshift. Recent astronomical observations[3] have reached excellent precision and provide a weighted mean value of the primordial deuterium abundance relative to hydrogen, $(\mathrm{D/H})_{\mathrm{obs}} = (2.527 \pm 0.030) \times 10^{-5}$, with a 1% uncertainty[3] (hereafter, quoted errors are at 68% confidence level unless stated otherwise). By contrast, theoretical predictions of D/H based on BBN, $(\mathrm{D/H})_{\mathrm{BBN}}$, are less clear: Coc *et al.*[5] report a value in agreement with observations, but with a higher uncertainty, while Pitrou *et al.*[4] report a value in tension with observations, albeit with a similar precision. Improving such predictions requires an accurate knowledge of the nuclear reaction rates involved in the synthesis of deuterium: specifically, production via the well-known p(n,γ)D process, and destruction via the D(d,n)^{3}He, D(d,p)^{3}H, and D(p,γ)^{3}He reactions. Of these, the D(p,γ)^{3}He reaction[4–6] carries the largest uncertainties because of insufficient experimental data at relevant BBN energies. While the D(p,γ)^{3}He cross section, or equivalently its S factor (see Methods "D(p,γ)^{3}He cross-section measurements at LUNA"), is well known[13] at low energies, $E \simeq 3 - 20$ keV (energies are in the centre of mass system unless stated otherwise), higher energy data[14–17] are affected by systematic uncertainties of 9% or more. In addition, a recent *ab-initio* theoretical calculation[18] disagrees at the level of 20-30% with a widely used S-factor best fit[19] to selected data sets[13–15,20] and at the level of ∼8% with a fit by Iliadis *et al.*[21]. As a result, BBN predictions of primordial deuterium abundance remain unsatisfactory, which calls for improved measurements of the D(p,γ)^{3}He reaction cross-section over a wide energy range[3–6,12].

The new measurement of the D(p,γ)^{3}He cross section discussed in this paper was performed at the LUNA-400kV accelerator[11], a world-leading facility to study nuclear reactions at the lowest energies frontier of nuclear astrophysics. The million-fold reduction in cosmic-ray muons of the deep-underground location[8] and a careful commissioning[10] of the experimental setup aimed at minimising all sources of systematic errors have led to D(p,γ)^{3}He cross-section data of unprecedented precision and with overall uncertainties below 3% over the measured energy region ($E = 32 - 263$ keV), relevant to BBN energies ($E = 30 - 300$ keV, see Methods). As shown in Figure 1, the new data represent a significant improvement compared to previous work[14,15,17]. Our new S-factor best fit (red solid line) implies a destruction of deuterium that is faster compared to the best fit[19] of previous experimental data (blue dashed curve), and slower compared to predictions based on the *ab-initio* calculation[18] (black dotted curve).

To explore the impact of our D(p,γ)^{3}He S-factor on the predicted primordial deuterium abundance, we used the second release[22] of the numerical BBN code PArthENoPE. Under the assumption of the ΛCDM model, with[23,24] $N_{\rm eff} = 3.045$, we performed a Bayesian likelihood analysis (see Methods) to derive $\Omega_{\rm b}h^2$ using the observed deuterium abundance, (D/H)$_{\rm obs}$, and the theoretical behaviour of (D/H)$_{\rm BBN}$ (now including the new LUNA data). We obtain $\Omega_{\rm b}h^2({\rm BBN}) = 0.02233 \pm 0.00036$. As shown in Figure 2, this value is a factor of 2 more precise than that obtained using a previous S factor[19] and now in much better agreement with the $\Omega_{\rm b}h^2$ based on CMB data[12] (see values in Table 1). The use of BBN deuterium alone as a baryometer has now approached a precision comparable to that obtained from CMB analyses[7,12]. The fact that the present-day values of $\Omega_{\rm b}h^2({\rm BBN})$ and $\Omega_{\rm b}h^2({\rm CMB})$ are fully consistent with each other (Table 1) offers evidence of the validity of the ΛCDM model adopted here.

We note that if we use the baryon density provided by the PLANCK Collaboration[7], we derive a theoretical prediction on deuterium abundance $(\mathrm{D/H})_{\mathrm{BBN}} = (2.52 \pm 0.03 \pm 0.06) \times 10^{-5}$, in excellent agreement with astronomical observations[3] $(\mathrm{D/H})_{\mathrm{obs}} = (2.527 \pm 0.030) \times 10^{-5}$. The quoted errors on $(\mathrm{D/H})_{\mathrm{BBN}}$ stem from the propagation of uncertainties in the baryon density (first error) and the nuclear rates (second error).

To probe the existence of physics beyond the ΛCDM model, we performed likelihood analyses in which both $\Omega_{\mathrm{b}}h^2$ and N_{eff} were left as free parameters. Since the deuterium abundance alone cannot be used to constrain $\Omega_{\mathrm{b}}h^2$ and N_{eff} when they are both varied, we considered two cases with additional inputs. In one case, hereafter (D+CMB), we used the deuterium abundance, both observed $(\mathrm{D/H})_{\mathrm{obs}}$ and predicted $(\mathrm{D/H})_{\mathrm{BBN}}$, combined with a Gaussian distribution of the CMB baryon density[7], with mean value and uncertainty as obtained by PLANCK without constraining N_{eff}; in the second case, hereafter (D+$\mathrm{Y_p}$), we used observed and predicted values of both the deuterium abundance and the ^{4}He mass fraction[25], Y_{p}, without constraining $\Omega_{\mathrm{b}}h^2$. Results are shown in Figure 3 as contour plots in the plane N_{eff} vs. $\Omega_{\mathrm{b}}h^2$. Numerical values at 68% confidence level are reported in Table 1. We note that, at the 99% confidence level, we obtain $N_{\mathrm{eff}} = 2.95^{+0.61}_{-0.57}$ and $N_{\mathrm{eff}} = 2.86^{+0.75}_{-0.67}$ for the two (D+CMB) and (D+$\mathrm{Y_p}$) cases, respectively. Our largest values of N_{eff} deviate by at most 20% from its standard value[23,24] $N_{\mathrm{eff}} = 3.045$. This implies a maximum amount of "dark radiation", due to particle species which are not foreseen by the standard model of particle physics, in agreement with PLANCK[7].

Although the (D+CMB) and (D+Y_p) cases discussed above lead to consistent outcomes, the (D+Y_p) result depends on the value of Y_p used. In our analysis, we adopted the value of Aver *et al.*[25], which is close to those of Peimbert *et al.*[26], Valerdi *et al.*[27], and the recommended value in Tanabashi *et al.*[2]. When the much higher Y_p value of Izotov *et al.*[28] is used, we obtain $N_{\rm eff} = 3.60^{+0.45}_{-0.43}$ (99% confidence level).

To conclude, we have measured the D(p,γ)^{3}He reaction cross section to an unprecedented precision of better than 3% by exploiting the million-fold reduction in cosmic-ray muons at LUNA. The new S factor has led to a remarkable improvement in the evaluation of the present-day baryon density, $\Omega_b h^2$, using standard Big Bang Nucleosynthesis alone. Our value is now in better agreement with the one derived from the analysis of the Cosmic Microwave Background anisotropies and provides further support to the standard cosmological model. When combined with additional inputs such as CMB baryon density or the primordial helium abundance, our data also provide a strong experimental foundation to constrain the amount of dark radiation.

Methods

D(p,γ)^{3}He cross-section measurements at LUNA. The cross section of the D(p,γ)^{3}He reaction ($Q = 5.493$ MeV) was measured in direct kinematics using a high intensity ($100-300$ μA) proton beam from the LUNA-400kV accelerator[11] over the full dynamic energy range $E_{\rm p} = 50-395$ keV, corresponding to centre-of-mass energies $E = 33-263$ keV. The beam was sent onto a windowless and extended gas target containing high-purity (99.999%) deuterium maintained at a pressure of $P = 0.3$ mbar by a system of three differential pumping stages. A copper calorimeter [29] at the end of the gas target stopped the beam and allowed its intensity to be measured. Gamma rays from the D(p,γ)^{3}He reaction were detected by a large high-purity germanium detector (HPGe) mounted in close geometry under the target chamber and facing its centre. Full details of the experimental setup and its commissioning have been described elsewhere[10].

For an extended gas target of length L, the cross section of the D(p,γ)^{3}He reaction can be expressed in terms of experimentally measurable quantities as:

$$\sigma(E) = \frac{N_\gamma(E)}{N_p \int_0^L \rho(z)\epsilon(z, E_\gamma)W(z)dz} \quad (1)$$

where $N_\gamma(E)$ is the net number of detected γ rays at a given interaction energy E, N_p is the number of incident protons, $\rho(z)$ is the number density of target atoms as a function of interaction position z along the target, $\epsilon(z, E_\gamma)$ is the γ-ray detection efficiency, and $W(z)$ is a term accounting for the angular distribution of the emitted γ rays.

Under experimental conditions at LUNA, the γ rays emitted by the D(p,γ)^{3}He reaction ($Q = 5.5$ MeV) have energies $E_\gamma = 5.5 - 5.8$ MeV, *i.e.* far away from the energy of the commonly used radioactive sources. Thus, a measurement of the detection (photo-peak) efficiency was performed using different-energy γ rays emitted in cascade from the well-known resonant reaction ^{14}N(p,$\gamma_1\gamma_2$)^{15}O. Efficiency corrections were validated by extensive Monte-Carlo simulations as described in detail in Mossa *et al.*[10].

To reduce the uncertainty on the final cross-section, we performed dedicated measurements to minimise the systematic errors associated with each term of Eq. (1).

A typical γ-ray spectrum taken at a proton beam energy $E_\mathrm{p} = 50$ keV is shown in Extended Data Figure 1. We note that the γ-ray background at LUNA is 3-4 orders of magnitude lower than on the Earth's surface[8] in the region of interest ($E_\gamma \simeq 5.5 - 5.8$ MeV) for the D(p,γ)^{3}He reaction. As a result, the counting statistical error could be kept below 1% at all beam energies. The main source of beam-induced background was due to the ^{19}F(p,$\alpha\gamma$)^{16}O reaction from the interaction of protons with fluorine contaminant usually present on collimators along the gas target and on the calorimeter[10] (beam dump). This beam-induced background ($E_\gamma < 7$ MeV) was found to be negligible at beam energies $E_\mathrm{p} < 250$ keV. At higher energies, approaching the well-known ^{19}F(p,$\alpha\gamma$)^{16}O resonance at $E_\mathrm{p} = 340$ keV, the beam-induced background was carefully accounted for in dedicated control runs in which (inert) ^{4}He gas was used instead of deuterium. A sample spectrum taken at the highest beam energy studied ($E_\mathrm{p} = 395$ keV) is shown in Extended Data Figure 2.

The cross-section results obtained at LUNA for the D(p,γ)^{3}He reaction are shown in Figure 1 (and summarised in Extended Data Table 1) in the form of the astrophysical S factor. This is defined as[30] $S(E) = E\sigma(E)\exp(2\pi\eta)$, where E is the energy of interaction, $\sigma(E)$ is the energy dependent cross section, and η is the Sommerfeld parameter $\eta(E) = \mathrm{Z}_1\mathrm{Z}_2\alpha(\mu c^2/2E)^{1/2}$ (where Z_1 and Z_2 are the atomic numbers of the interacting nuclei, α is the fine structure constant, μ is the reduced mass, and c is the speed of light). We achieved an overall systematic uncertainty lower than 3%, with main contributions arising from uncertainties in beam current (1%), target density profile (1.1%), and efficiency (2%), as described in Mossa *et al.*[10]. We note that our new experimental data are close to a previous fit[21] (not shown in Fig. 1) based on a Bayesian analysis of previous selected experimental data sets.

Our new S factor was used together with other data sets[13–16,31–33] to arrive at the best fit:

$$S(E) = 0.2121 + 5.973\times10^{-3}\,E + 5.449\times10^{-6}\,E^2 - 1.656\times10^{-9}\,E^3 \quad [\mathrm{eV\,b}] \qquad (2)$$

(with E in keV) shown in Fig. 1 (red solid line). The fit was performed over a broad energy range $E_{\mathrm{cm}} = 2-2000$ keV, following the approach of Serpico *et al.*[34]. At BBN energies, the fit is entirely dominated by the new LUNA data reported here, thanks to their increased precision compared to previous works. We obtain a reduced χ^2 of 1.049. The uncertainties on the fit (red band in Fig. 2) are given by:

$$(\Delta S(E))^2 = 1.4\times10^{-5} + 2.97\times10^{-8}E^2 + 4.80\times10^{-13}E^4 + 1.12\times10^{-19}E^6 \quad [(\mathrm{eV\,b})^2] \quad (3)$$

(with E in keV). The correlation among data points of the same data set was properly taken into account[34] by introducing a single normalization factor for each data set, constrained by the so-called penalty factor in the χ^2.

As the universe expands, BBN takes place over a temperature range of the nucleon-photon plasma $k_{\mathrm{B}}T \sim 100 - 20$ keV, with k_{B} being the Boltzmann constant. To better assess the energy range where precise measurements of the D(p,γ)^{3}He cross section have the largest impact in improving the accuracy of theoretical predictions of primordial deuterium abundance relative to hydrogen, (D/H)$_{\mathrm{BBN}}$, we used a *sensitivity function* (see for example Nollett *et al.*[35]), defined as the ratio of the logarithmic derivatives of the D/H abundance and the corresponding S factor:

$$\zeta(E) = \frac{\delta \log(\mathrm{D/H})_{\mathrm{BBN}}}{\delta \log S(E)} \tag{4}$$

Specifically, we varied the S factor in 10 keV energy bins, over a broad energy region of $10 - 500$ keV, and calculated the corresponding thermal rate (obtained by convolution with the Maxwell-Boltzmann distribution) bin by bin as a function of energy. The corresponding yield of deuterium was obtained using the PArthENoPE code[22] (see also Methods "Bayesian Likelihood Analysis"). The results are shown in Extended Data Figure 3. We note that the sensitivity curve remains above 25% of the maximum variation in a range $E = 20 - 240$ keV, with the deuterium abundance being most sensitive to the D(p,γ)^{3}He cross section at $E \simeq 80$ keV, i.e. in a region where our precision underground measurements are essential. Our values of the D(p,γ)^{3}He thermal rate and their uncertainties are provided in Extended Data Table 2.

Bayesian Likelihood Analysis. To study the effect of the new LUNA D(p,γ)^{3}He S factor on primordial deuterium produced during Big Bang Nucleosynthesis, we have computed the corresponding thermal rate and updated it (Pisanti *et al.*, in preparation) in the second release of the BBN code PArthENoPE[22]. The rates of the D(d,n)^{3}He and D(d,p)^{3}H have also been updated following the publication of new data sets[36], although their inclusion has a negligible effect (Pisanti *et al.*, in preparation) on the uncertainty on the (D/H)$_{\rm BBN}$ value presented in this work. Starting from conditions of nuclear statistical equilibrium, PArthENoPE solves a set of coupled ordinary differential equations that follow the departure from chemical equilibrium of nuclear species and determines their asymptotic abundances as a function of several input cosmological parameters such as the baryon density $\Omega_{\rm b}h^2$, the number of effective neutrino species $N_{\rm eff}$, the value of the cosmological constant, and neutrino chemical potentials (see, e.g. Pisanti *et al.*[37] for details).

The reduced uncertainty of the LUNA results affects the precision of BBN deuterium prediction and can constrain the baryon density. In a first analysis we assume a standard BBN scenario and fix the value of the relativistic degrees of freedom to photons and three active neutrino species ($N_\nu = 3$) corresponding to a contribution $N_{\rm eff} = 3.045$ in the energy density of neutrinos, conventionally given[6] as $\rho_\nu = \frac{7}{8}(\frac{4}{11})^{4/3}\rho_\gamma N_{\rm eff}$ (with ρ_γ being the photon density). We use (D/H)$_{\rm BBN}$ as a function of $\Omega_{\rm b}h^2$ and the deuterium abundance inferred from astronomical observations (D/H)$_{\rm obs}$. The likelihood function is:

$$\mathcal{L}_{\rm D+3\nu}(\Omega_{\rm b}h^2) = \exp\left[-\frac{[({\rm D/H})_{\rm BBN}(\Omega_{\rm b}h^2) - ({\rm D/H})_{\rm obs}]^2}{2[\sigma^2_{\rm BBN}(\Omega_{\rm b}h^2) + \sigma^2_{\rm obs}]}\right] \quad (5)$$

where $\sigma_{\rm BBN}$ is the propagated error on the deuterium yield due to the experimental uncertainties on nuclear reactions, and $\sigma_{\rm obs}$ is the uncertainty on the astronomical observations.

We performed two other analyses in which both $\Omega_{\rm b}h^2$ and $N_{\rm eff}$ were free to vary and constrained the likelihood function $\mathcal{L}_{\rm D}(\Omega_{\rm b}h^2, N_{\rm eff})$ with other astrophysical inputs. In one case, (D+CMB), we used the deuterium abundance (both predicted and observed) and assumed a Gaussian distribution on the baryon density, $\mathcal{L}_{\rm CMB}(\Omega_{\rm b}h^2)$, corresponding to the latest PLANCK value[7]

$\Omega_b h^2(\mathrm{CMB}) = 0.02224 \pm 0.00022$, obtained without constraining N_{eff}. The likelihood function is now expressed as:

$$\mathcal{L}_{\mathrm{D+CMB}}(\Omega_b h^2, N_{\mathrm{eff}}) = \mathcal{L}_{\mathrm{CMB}}(\Omega_b h^2) \exp\left[-\frac{[(\mathrm{D/H})_{\mathrm{BBN}}(\Omega_b h^2, N_{\mathrm{eff}}) - (\mathrm{D/H})_{\mathrm{obs}}]^2}{2[\sigma^2_{\mathrm{BBN}}(\Omega_b h^2, N_{\mathrm{eff}}) + \sigma^2_{\mathrm{obs}}]}\right] \quad (6)$$

In the other case, (D+Y_p), we used BBN predictions and observed abundances of both deuterium and ^{4}He mass fraction ($Y_p = 0.2449 \pm 0.0040$ from astronomical observations[25]) together with the most recent[2] neutron lifetime ($\tau_n = 879.4 \pm 0.6$ s), which carries the largest uncertainty on the theoretical prediction of ^{4}He primordial abundance. No prior distribution was assumed on the baryon density. In this case, the likelihood function is the product of two exponential functions: one for deuterium as that appearing in Eq. (6) and a similar one for ^{4}He.

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Specifica TAsP.

Author Contributions The experiment at LUNA was proposed by CG and coordinated by FC and DT. PC, CG, SZ and VM planned the setup; SZ and PC developed the Monte Carlo simulations; SZ, FC, PC, CG, VM, KS and FF led the data analysis. Other authors contributed to the data taking over a period of 2 years and to discussion and interpretation of the results obtained. MJ also has overall responsibility for the accelerator operations and the underground site. GM and OP performed all BBN calculations and Bayesian analyses. LEM, AK, MV performed *ab-initio* calculations. MA, FC, CG, GM and OP also wrote the paper.

Competing interests The authors declare no competing financial interests.

Data availability Experimental data taken at LUNA are proprietary to the Collaboration but can be made available from the corresponding authors upon reasonable request. Values of the thermonuclear reaction rate for smaller temperature steps can be obtained upon request to O.P.

Code availability The PArthENoPE code used for BBN calculations can be made available upon request to O.P.

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Table 1: **Mean values and 68% confidence-level ranges for the baryon density $\Omega_b h^2$ (with relative uncertainties δ) and the effective number of neutrino species $N_{\rm eff}$.** The first two lines show the results obtained from the likelihood analyses performed in this study, without and with the new D(p,γ)^{3}He S factor obtained at LUNA and with $N_{\rm eff}$ fixed to its standard value[23,24] of 3.045. The third and fourth lines show results obtained, respectively, using CMB data alone[12] (CMB+3ν) and CMB data combined with the theoretical dependence of primordial ^{4}He on baryon density[7] (PLANCK+3ν). The last two lines correspond to cases in which both $\Omega_b h^2$ and $N_{\rm eff}$ are left as free parameters and the likelihood functions are constrained by either the deuterium abundance and a prior distribution on $\Omega_b h^2$, (D+CMB) case, or the observed and predicted abundances of both deuterium and helium, (D+Y_p) case (in both cases the predicted deuterium abundance takes into account our new LUNA results; see Methods for details).

	$\Omega_b h^2$	δ [%]	$N_{\rm eff}$
D+3ν (without LUNA data)	0.02271 ± 0.00062	2.73	3.045
D+3ν (with new LUNA data)	0.02233 ± 0.00036	1.61	3.045
CMB+3ν	$0.02230 \pm 0.00021^{a)}$	0.94	3.045
PLANCK+3ν	0.02236 ± 0.00015	0.67	3.045
D+CMB	0.02224 ± 0.00022	0.99	2.95 ± 0.22
D+Y_p	0.0221 ± 0.0006	2.71	$2.86^{+0.28}_{-0.27}$

$^{a)}$Quoted in Fields *et al.*[12] as 0.022298 ± 0.000214.

Extended Data Table 1: **Astrophysical *S* factors for the D(p,γ)^{3}He reaction at the measured centre-of-mass energies.** Values of the astrophysical S factor as measured at LUNA over the full energy range explored. Statistical (σ_{stat}) and systematic (σ_{sys}) uncertainties at 68% confidence level are also reported. The statistical uncertainty is typically negligible except at the lowest energy point (3.6%), where it dominates over the systematic uncertainty (2.7%). Systematic uncertainties remain below 3% at all energies.

E [keV]	$S(E)$ [eV b]	σ_{stat} [eV b]	σ_{sys} [eV b]
32.4	0.386	0.014	0.010
66.7	0.627	0.009	0.016
99.5	0.850	0.008	0.021
115.9	0.966	0.009	0.024
132.9	1.133	0.004	0.031
149.3	1.223	0.006	0.031
166.1	1.375	0.004	0.036
182.7	1.475	0.006	0.037
199.5	1.648	0.003	0.043
222.8	1.791	0.006	0.045
232.9	1.866	0.012	0.051
252.9	2.073	0.012	0.052
262.9	2.156	0.020	0.054

Extended Data Table 2: **Thermonuclear reaction rate for the D(p,γ)^{3}He reaction.** Values of the thermonuclear reaction rate R obtained from our best fit S factor of the D(p,γ)^{3}He reaction as a function of temperature in GK. Low- and high-rates are quoted at the 1σ level.

T [GK]	R [cm^{3}mol^{-1}s^{-1}]	R_{low} [cm^{3}mol^{-1}s^{-1}]	R_{high} [cm^{3}mol^{-1}s^{-1}]
0.001	1.37×10^{-11}	1.35×10^{-11}	1.39×10^{-11}
0.005	2.57×10^{-5}	2.53×10^{-5}	2.62×10^{-5}
0.01	1.53×10^{-3}	1.51×10^{-3}	1.56×10^{-3}
0.05	9.08×10^{-1}	8.94×10^{-1}	9.22×10^{-1}
0.10	5.74×10^{0}	5.65×10^{0}	5.84×10^{0}
0.50	1.29×10^{2}	1.26×10^{2}	1.32×10^{2}
1.0	3.63×10^{2}	3.52×10^{2}	3.74×10^{2}
1.5	6.32×10^{2}	6.09×10^{2}	6.56×10^{2}
2.0	9.20×10^{2}	8.79×10^{2}	9.62×10^{2}
3.0	1.52×10^{3}	1.43×10^{3}	1.61×10^{3}
4.0	2.11×10^{3}	1.95×10^{3}	2.28×10^{3}
5.0	2.67×10^{3}	2.40×10^{3}	2.93×10^{3}
6.0	3.16×10^{3}	2.76×10^{3}	3.55×10^{3}
7.0	3.56×10^{3}	3.00×10^{3}	4.12×10^{3}
8.0	3.85×10^{3}	3.09×10^{3}	4.61×10^{3}
9.0	4.01×10^{3}	3.02×10^{3}	5.01×10^{3}
10.0	4.02×10^{3}	2.75×10^{3}	5.30×10^{3}

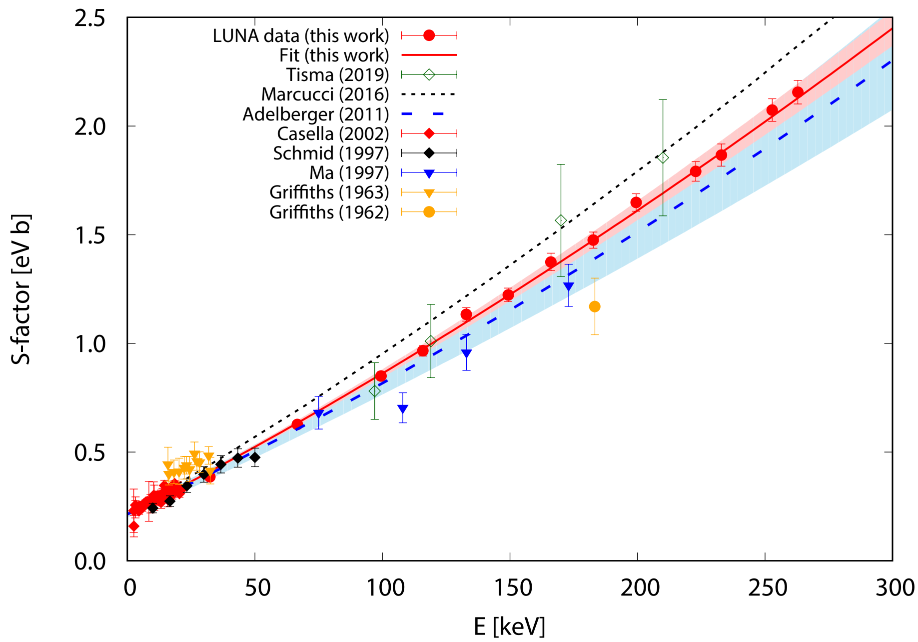


Figure 1: ***S* factor of the D(p,γ)^{3}He reaction.** At BBN energies ($E_{\rm cm} \simeq 30 - 300$ keV), the new LUNA results (filled red circles) indicate a faster deuterium destruction compared to a best fit[19] (blue dashed line) of previous experimental data, but a slower destruction compared to theoretical calculations[18] (black dotted line). At BBN energies, the best fit (red solid line, Eq. 2) obtained in this work is entirely dominated by the LUNA data. The fit includes all experimental data[13–16, 31–33] (note that those by Warren *et al.*[32] and Geller *et al.*[33] lie outside the energy range shown here). Bands represent the 68% confidence level.

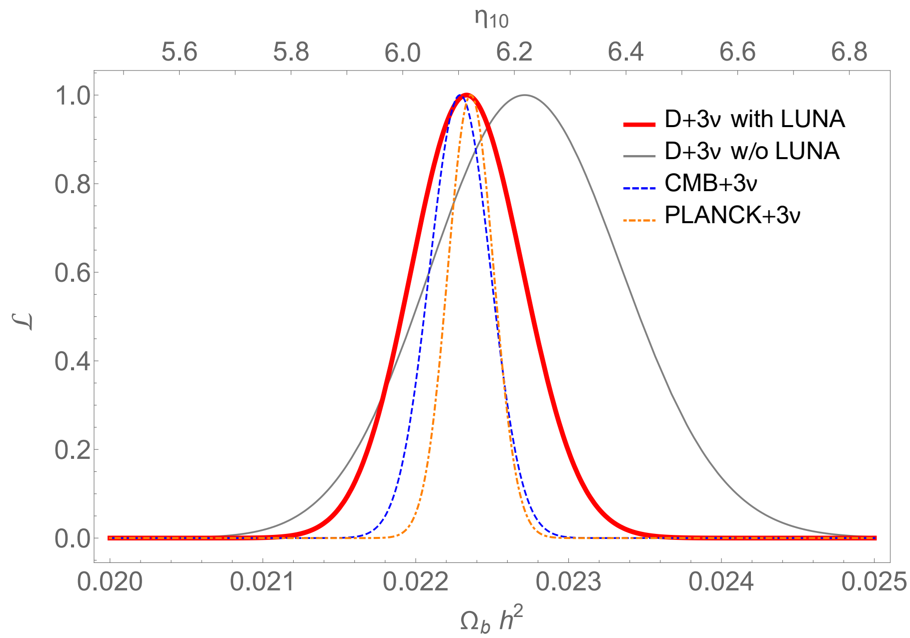


Figure 2: **Likelihood distribution of the baryon density (lower *x*-axis) and baryon-to-photon ratio (η_{10}, upper *x*-axis).** The red curve (D+3ν with LUNA) shows the distribution of the baryon density obtained using the new LUNA S factor for the predicted deuterium abundance $(\mathrm{D/H})_{\mathrm{BBN}}$. Note the factor of 2 reduction in the uncertainty, as compared to the distribution based on previous S factor[19] (grey curve, D+3ν w/o LUNA). Our new determination of $\Omega_{\mathrm{b}}h^2$ is now in much better agreement with the value obtained from CMB data alone[12] (blue dashed curve, CMB+3ν) and with the best determination of baryon density obtained by PLANCK[7] from CMB data combined with additional observational inputs and with the theoretical dependence of primordial ^{4}He on baryon density (orange dot-dashed curve, PLANCK+3ν).

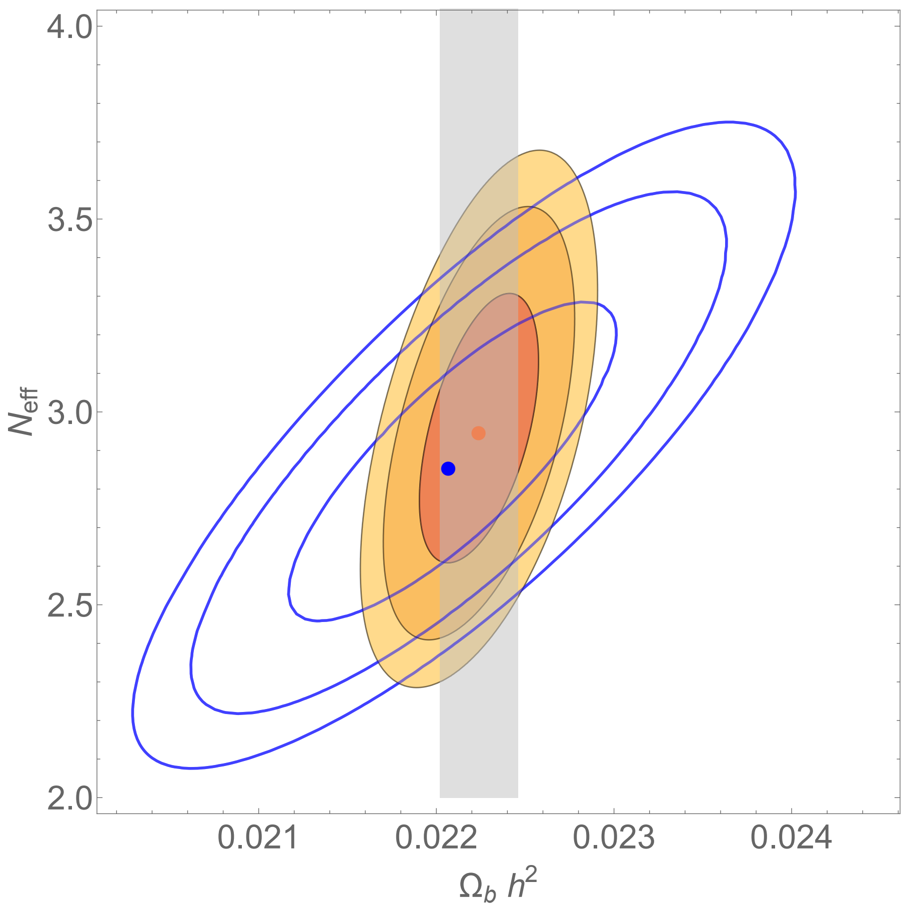
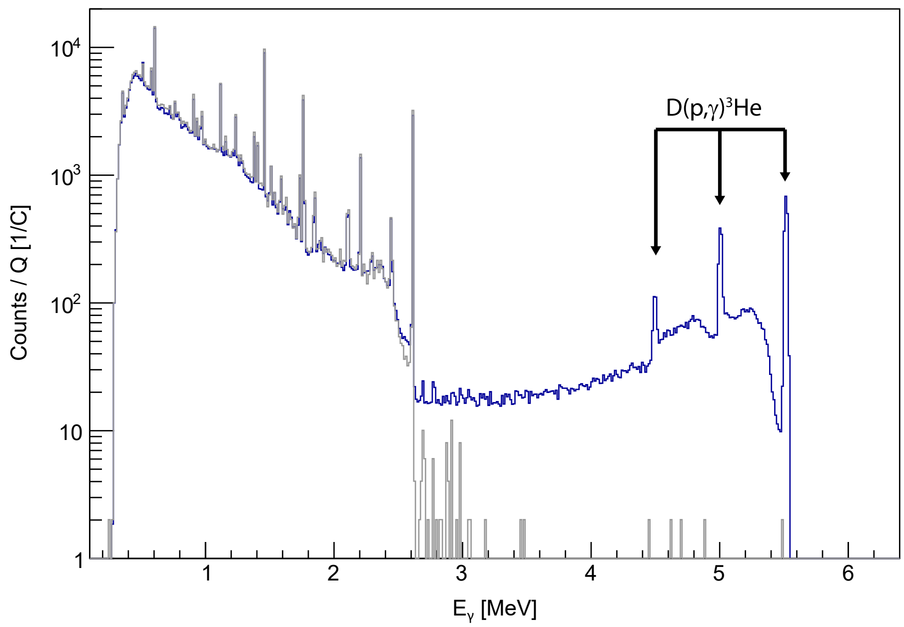
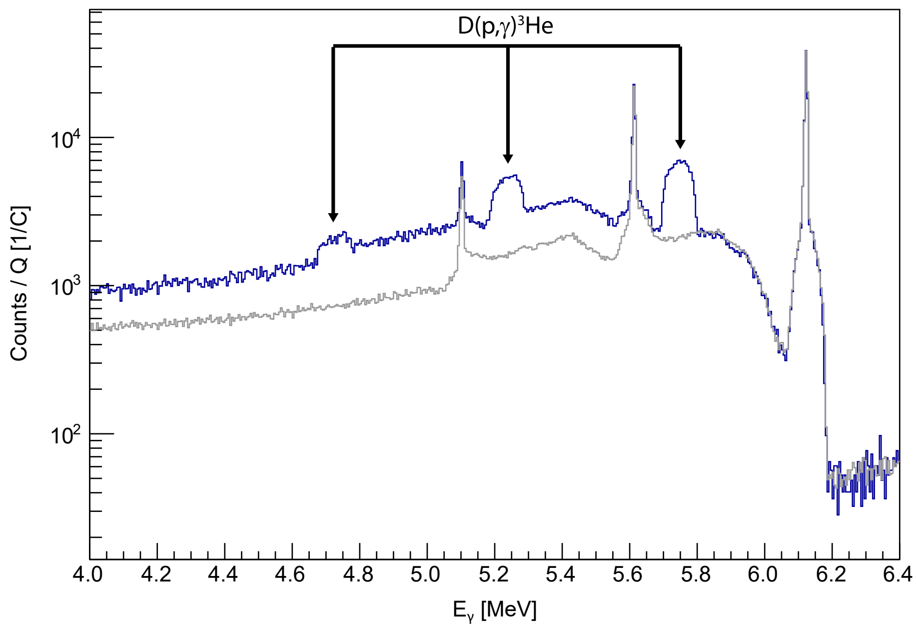


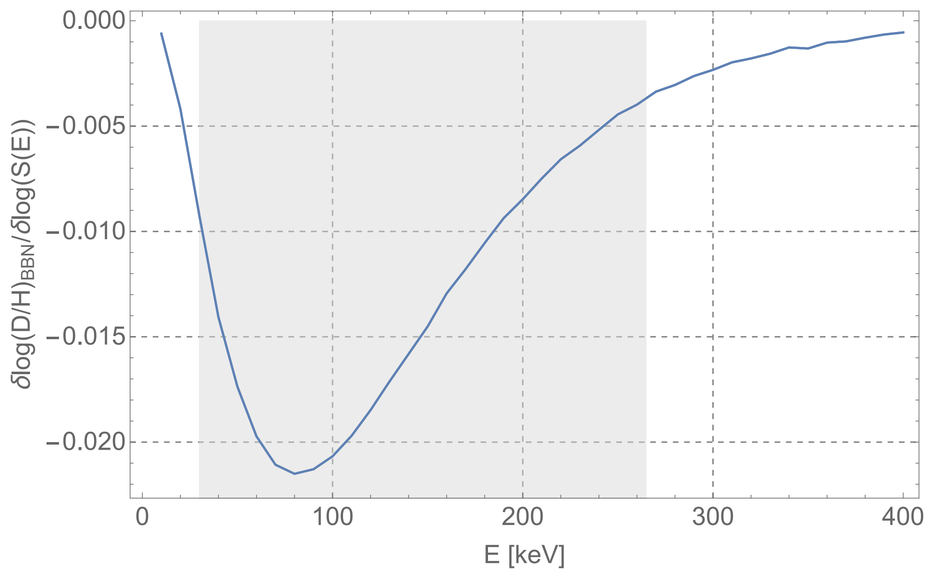
Figure 3: **Likelihood contours (at 68%, 95% and 99% confidence level) on the $N_{\rm eff}$ vs. $\Omega_{\rm b}h^2$ plane.** Orange filled contours are obtained for the D+CMB case using the observed deuterium abundance[3] $(D/H)_{obs}$ and the adopted PLANCK distribution on baryon density[7] (grey vertical band at the 68% confidence level). Blue contours correspond to the D+Y_p case, as obtained from a likelihood analysis with observed abundances of deuterium[3] and ^{4}He mass fraction[25], $Y_{\rm p}$, and the corresponding BBN theoretical predictions (see Methods for details). Central values for each case are indicated by dots.



Extended Data Figure 1: **Typical γ-ray spectrum obtained underground with the HPGe detector at proton beam energy $E_{\rm p} = 50$ keV.** Typical γ-ray spectrum (blue) obtained with the deuterium gas target at $P = 0.3$ mbar, clearly showing the full-energy, single- and double-escape peaks from the D(p,γ)^{3}He reaction. The continuum is mainly due to Compton scattering events in which photons deposit only part of their energy in the detector. In grey is the beam-induced background spectrum acquired in the control run under the same experimental conditions but with an inert ^{4}He gas target. Both spectra are normalised to the integrated beam current. The region of interest ($E_\gamma \sim 4.5 - 5.8$ MeV) is essentially background free thanks to the million-fold shielding[8] from cosmic-ray muons obtained at the LUNA underground laboratory.



Extended Data Figure 2: **Typical γ-ray spectrum taken at proton beam energy $E_\mathrm{p} = 395$ keV.** In blue, γ-ray spectrum obtained with the deuterium gas target at $P = 0.3$ mbar (the peaks from the D(p,γ)^{3}He reaction are broadened by the Doppler effect at this higher beam energy). In grey, beam-induced background spectrum (acquired with an inert ^{4}He gas target) due to the ^{19}F contaminant (see text). Its contribution was subtracted leading to net counts on the full energy peak with a statistical uncertainty of 0.9%. Both spectra are normalised to the integrated beam current.



Extended Data Figure 3: **Sensitivity of the primordial deuterium abundance to the D(p,γ)^{3}He reaction cross section as a function of centre-of-mass energy.** The greatest sensitivity is obtained around $E = 80$ keV, where underground measurements are especially effective. The grey area represents the energy region explored at LUNA (see Methods for details).